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ASSESSMENT OF ULTRA-HIGH PERFORMANCE FIBRE REINFORCED CONCRETE- NORMAL STRENGTH CONCRETE OR HIGH STRENGTH CONCRETE COMPOSITE MEMBERS IN CHLORIDE ENVIRONMENT

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ABSTRACT

The purpose of this study was to investigate the performance of composite members of ultra-high performance fibre-reinforced concrete (UHPFRC) and normal strength or high strength concrete (NSC/HSC) in chloride environments. Experimental studies were carried out on UHPFRC-NSC/HSC prisms in order to investigate the effect of dry and wet cycles on the flexural capacity of those composite members. Each prism specimen was designed with the UHPFRC layer in tension and the NSC/HSC layer in compression. Three fibre volume contents (1%, 1.5%, and 2%) were investigated. The test results revealed that the degradation in the flexural capacity of UHPFRC-NSC/HSC specimens after exposure to chloride ion solutions was between 4% and 17%. The results also revealed that the effect of using high strength concrete versus normal strength concrete in the composite prisms was negligible. In addition, the results revealed that the degradation in flexural capacity was reduced by an increase in the fibre volume content.

Keywords: Durability, Ultra High Performance, Fibre Reinforced Concrete, Composite Members

1. INTRODUCTION

Corrosion of steel reinforcements is one of the most common causes of degradation in reinforced concrete structures. According to a 2013 report of U.S. infrastructure [1], approximately one in nine bridges in the United States was rated as structurally deficient, and corrosion of the reinforcing steel was listed as a significant contributor to structural deficiencies. Chloride-induced corrosion of reinforcing steel is considered the primary cause of deterioration in concrete structures such as bridges, parking garages and marine structures. This affects the serviceability and the ultimate strength of concrete elements. Corrosion products exert stresses within the concrete, resulting in the formation of cracks along the reinforcing bars. These cracks weaken the bond and the anchorage between the steel and the concrete, leading to cracking and spalling in the concrete which in turn facilitates the ingress of oxygen and moisture to the reinforcing steel and increases the rate of corrosion.

The repair and rehabilitation of structures that are exposed to corrosive salt conditions in marine environments and cold-climate regions costs billions of dollars each year. Durability has also become an important characteristic of reinforced concrete infrastructures. Innovative and cost-effective systems must be developed in order to enhance the durability of reinforced concrete structures. A system combining normal strength concrete and high strength concrete (NSC/HSC) with ultra-high performance fibre-reinforced concrete (UHPFRC) in a composite construction was proposed by the authors [2] with the intention of optimizing the use of the properties of both materials. In this composite system, UHPFRC was used in the parts of the structure that require high mechanical loading and/or low permeability to harmful substances, and NSC/HSC was used in all other parts.

The proposed composite “UHPFRC-NSC/HSC” system can be used for the effective construction of new structures and the rehabilitation of existing structures. Test results revealed that the performance of the proposed composite system, in terms of flexural and shear capacity, was successfully enhanced. The composite beams failed in shear at a force that is 1.6 to 2.0 times higher than that of the resistance of the NSC/HSC beams [2]. The test results also revealed that the bond strength between the two concrete material layers (UHPFRC and NSC/HSC) was significantly high, rendering the addition of shear connectors unnecessary [2].

Numerous studies have indicated that the ingress of chloride ions in concrete structures such as marine structures exposed to seawater, parking garages and highway structures exposed to de-icing salt is the most prominent mechanism of concrete deterioration. The penetration of chlorides in reinforced concrete structures accelerates reinforcement corrosion by destroying the passive layer around the steel reinforcement surface [3, 4]. The sequence of drying and wetting cycles also affects the chloride ingress into concrete. Chloride penetrates concrete through different mechanisms [5]. These mechanisms include absorption, diffusion, chloride binding, permeation, wicking and dispersion. Diffusion and absorption are the most significant mechanisms for structures exposed to dry and wet cycles [5].

The UHPFRC-NSC/HSC composite member is the first of its kind and will be very useful for both the concrete technology and economic construction of UHPFRC. In order to investigate the durability of this composite system, further investigation was required. The objective of this research project was to study the effect of chloride on the flexural capacity of UHPFRC-NSC/HSC composite members. The flexural capacity was evaluated by performing four-point un-notched bending tests in accordance with ASTM C1609 [6]. The effect of fibre volume content and the composite section UHPFRC-NSC or UHPFRC-HSC is discussed.

2. RESEARCH SIGNIFICANCE

The composite UHPFRC-NSC/HSC member is a new system that was recently developed by the authors. In order to understand the effect of harsh environmental conditions on the mechanical properties of this system, this paper investigates the effect of wet and dry cycles using salt water on the performance of composite UHPFRC-NSC/HSC members.

3. EXPERIMENTAL PROGRAM

3.1 Material properties

The UHPC mixture used in this study is a commercial product, Ductal®, which is composed of premixed powder, water, and superplasticizer. The premixed powder includes cement, silica fume, ground quartz, and sand. Table 1 shows the typical composition of this material. Ductal® UHPFRC suggests the use of straight steel fibre geometry (13 mm length x 0.2 mm diameter) with a tensile strength above 2500 MPa.

Table 1 Typical composition of Ductal®

Material	kg/m^3	Percentage by weight
Portland Cement	712	28.5
Fine Sand	1020	40.8
Silica Fume	231	9.3
Ground Quartz	211	8.4
Superplasticizer	30.7	1.2
Water	109	4.4

3.2 Preparation of test specimens

The UHPFRC was mixed in a 250 L capacity shear mixer. When casting composite members, the setting time is longer for UHPFRC than for the NSC, HSC, and the UHPC premix provided by Lafarge Inc. without an accelerator.

For this reason, the members were cast upside down. The NSC/HSC layer was cast first, and then the UHPFRC layer was cast on top of the NSC/HSC layer without any surface preparation before casting. After casting, the composite specimens were sprayed with water and covered with plastic sheets and were stored at room temperature for 28 days.

A total of 36 specimens distributed in six series were tested to determine the effect of wet-dry cycles on the flexural tensile strength of UHPFRC-NSC/HSC. The bending tests were performed on concrete prisms 50 x 76 x 355 mm in size. The composite UHPFRC-NSC/HSC prisms were composed of a 25 mm NSC/HSC layer at the top and a 25 mm UHPFRC layer at the bottom. The NSC/HSC and UHPFRC layers were cast at the same time; the NSC/HSC layer was cast first and then the UHPFRC layer was cast on top. For each series, three specimens were stored at room temperature ($22\,C^{o}$) as control specimens, and three specimens were immersed in water containing 5% NaCl at $20\,C^{o}$ for three days and dried at room temperature ($22\,C^{o}$) for four days (for a total of 365 days). After 365 days, the samples were immersed in water containing 5% NaCl at $20\,C^{o}$ for one week and dried at room temperature ($22\,C^{o}$) for one week (for a total of 235 days). The solution was changed every eight weeks.

3.3 Mechanical properties of concrete

The compressive strength, f_c', of UHPFRC, NSC and HSC was obtained through the compressive testing of cylindrical specimens with a diameter of 100 mm and height of 200 mm in accordance with ASTM C39/C39M [6]. The splitting tensile strength of UHPFRC, NSC and HSC was obtained in accordance with ASTM C496/C596M [7]. The cylindrical specimens were cast at the same time as the test prisms. After casting, the UHPFRC specimens were sprayed with water, covered with plastic sheets and stored at room temperature for 28 days. At the end of the curing period, the cylindrical specimens were stored at room temperature and were tested on the same day as the concrete prisms.

The tensile strength, f_{sp}, of UHPFRC, NSC and HSC was obtained through the split cylinder testing of specimens with a diameter of 100 mm and height of 200 mm. The ends of the cylinders were ground flat to remove the weak paste layers and to ensure that the cylinders were uniformly and axially loaded. Table 2 lists the average values of the compressive strength and split cylinder tests for all UHPFRC-NSC/HSC members.

The flexural tensile strength of composite prisms was determined using four-point un-notched bending tests in accordance with ASTM C1609 [8]. The prisms were loaded at a rate of 0.05 mm/min. Measurements were obtained using the MTS machine and the load-deflection curve was drawn. Fig. 1 shows the test setup for the composite prisms.

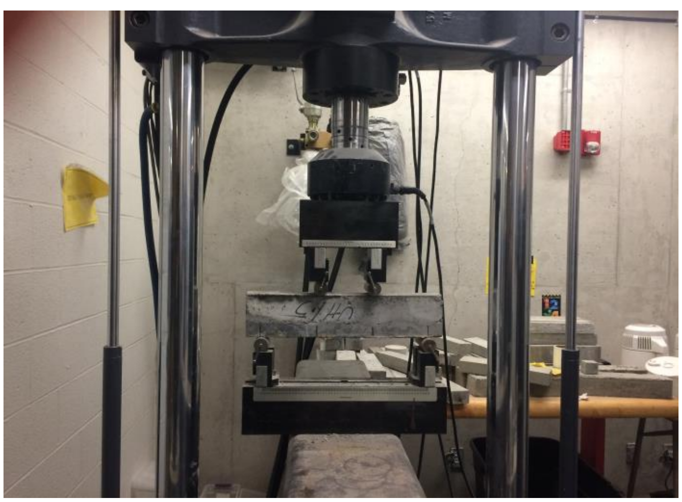

Figure 1: Test setup of composite prisms

4. ANALYSIS AND DISCUSSION OF RESULTS

4.1 Flexural capacity

The key results obtained from the prism tests are summarized in Tables 2 and 3. The results indicate that the reduction in the flexural capacity due to wet and dry cycles was between 4% and 9% for composite specimens with 1.5% and 2% fibre volume content, and between 13% and 17% for composite specimens with 1% fibre volume content. Table 2 shows the average deflection at first crack, average load at first crack, average deflection at peak load, average peak load and toughness. The first crack load and the first crack deflection represent the load when the first crack initiated and the corresponding deflection, while the peak load and peak deflection represent the peak load and the corresponding deflection. The average first crack load was calculated by obtaining the mean of all deflections at first crack load. The average first crack load is the load corresponding to the average deflection calculated by interpolating the two nearest points on the load-deflection curves. A similar procedure was used to calculate the average peak load and corresponding deflection.

Table 2: Flexural test results

Series	Average Compressive Strength (MPa)	Average Splitting Tensile Strength (MPa)	Average Deflection at First Crack (mm) (CV)	Average Load at First Crack (kN)	Average Deflection at Peak Load (mm) (CV)	Average Peak Load (kN)	Toughness (kN-mm)
UN1	N51.197 U159.985	N3.029 U11.169	0.651 (0.064)	8.811	0.774 (0.069)	9.682	14.773
UN1S			0.604 (0.156)	7.331	0.731 (0.045)	7.961	12.739
UN1.5	N51.197 U169.838	N3.029 U14.768	0.836 (0.087)	11.297	0.969 (0.011)	11.527	17.740
UN1.5S			0.753 (0.061)	9.464	0.924 (0.029)	10.878	16.228
UN2	N51.197 U168.001	N3.029 U15.534	0.947 (0.032)	12.185	1.342 (0.076)	14.293	20.381
UN2S			0.798 (0.88)	10.661	1.199 (0.103)	13.712	19.394
UH1	H70.078 U181.907	H4.216 U13.002	0.623 (0.024)	10.125	0.796 (0.037)	11.347	16.439
UH1S			0.585 (0.054)	8.699	0.780 (0.057)	9.975	14.249
UH1.5	H70.078 U170.189	H4.216 U15.635	1.018 (0.022)	14.129	1.158 (0.097)	14.645	21.624
UH1.5S			0.847 (0.036)	12.869	0.989 (0.012)	13.380	19.133
UH2	H70.078 U191.838	H4.216 U16.275	0.809 (0.041)	14.389	1.198 (0.032)	17.074	24.871
UH2S			0.771 (0.039)	13.303	1.078 (0.103)	16.257	22.479

CV=Coefficient of Variation

Table 3: Flexural capacity of test specimens

Beam specimen	Fibres %	Maximum Flexural capacity $M_{\exp}$ (kN.mm)	Decrease in Resistance $\left(\frac{M_{\exp}-M_{\exp 0}}{M_{\exp 0}}\right)$ (%)
UN1	1.0	491.820	
UN1S	1.0	404.393	17.76
UN1.5	1.5	585.751	
UN1.5S	1.5	552.602	5.63
UN2	2.0	726.059	
UN2S	2.0	696.544	4.06
UH1	1.0	576.402	
UH1S	1.0	496.571	13.85
UH1.5	1.5	743.966	
UH1.5S	1.5	679.704	8.64
UH2	2.0	867.334	
UH2S	2.0	825.556	4.78

Figure 2 shows the cracking behaviour of UHPFRC-NSC (UN) and UHPFRC-HSC (UH) prisms. Following the initiation of the first crack in the prisms, the crack propagated slowly and the prisms were able to carry the load after failure. The average peak load for UN control prisms with 1%, 1.5% and 2% fibre volume content was 9.682, 11.527 and 14.293 kN (respectively), while the average peak load for UHPFRC-NSC prisms subjected to wet and dry cycles (UNS) with 1%, 1.5% and 2% fibre volume content was 7.961, 10.878 and 13.712 kN (respectively). Table 3 shows that the reduction in the flexural capacity due to dry and wet cycles of prisms with 1% fibre content was 17.17% while the reduction in the flexural capacity of prisms with 1.5% and 2% fibre content was 5.63% and 4.06%, respectively. These results indicate that the increase in fibre content (from 1% to 1.5%) significantly enhanced the flexural capacity of UNS prisms. The average peak load for UH control prisms with 1%, 1.5% and 2% fibre volume content was 11.347, 14.645 and 17.074 kN (respectively), while the average peak load for UHPFRC-HSC prisms subjected to wet and dry cycles (UHS) with 1%, 1.5% and 2% fibre volume content was 9.975, 13.380 and 16.257 kN (respectively). Table 3 shows that the reduction in the flexural capacity due to dry and wet cycles of prisms with 1% fibre content was 13.85%, while the reduction in the flexural capacity of prisms with 1.5% and 2% fibre content was 8.64% and 4.78%, respectively. These results indicate that the increase in the fibre content (from 1% to 1.5%) significantly enhanced the flexural capacity of UHS prisms.

The toughness of concrete prisms was calculated by estimating the area under the load-deflection curve. The results revealed that the wet-dry cycles caused a slight reduction in the toughness of the prisms (as shown in Table 2). The average reduction of the toughness of prisms with 1%, 1.5%, and 2% fibre volume content was 13%, 10%, and 7% (respectively). These results indicate that addition of steel fibres improved the toughness of the prisms subjected to wet-dry cycles compared to control prisms.

4.2 Load-deflection response

Figures 3 and 4 show the average load deflection of UN and UH prisms. The deflection of the prisms increased in a linear fashion and was proportional to the applied load, even after the initiation of cracks. The load–deflection curves of all the composite prisms showed similar behaviour and were not significantly influenced by the wet-dry cycles. The composite prisms subjected to wet and dry cycles were able to carry the applied load and the stiffness was only slightly degraded after the initiation of the cracks. This behaviour can be attributed to the high stiffness of the UHPFRC layer supporting the NSC/HSC layer. The figures also show high degradation in the UHS prisms compared to the UNS prisms after peak load. This behaviour can be attributed to the brittleness of the HSC layer compared to the NSC layer.

(a) UN1S

(b) UH1S

(c) UN1.5S

(d) UH1.5S

(e) UN2S

(f) UH2S

Figure 2 Cracking pattern for UHPFRC-NSC/HSC flexural prisms

5. CONCLUSIONS

A system combining normal strength and high strength concrete (NSC/HSC) with ultra-high performance fibre-reinforced concrete (UHPFRC) in a composite construction was proposed by the authors with the intention of optimizing the use of the properties of both materials. This composite system will be very useful for both the concrete technology and economic constructions of UHPFRC. This study involved an experimental investigation of the performance of UHPFRC-NSC/HSC composite prisms following exposure to chloride ion solutions. The following conclusions were drawn from the test results:

- The test results revealed that the degradation in the flexural capacity of UHPFRC-NSC/HSC specimens after exposure to chloride ion solutions was between 4% and 17%.
- The test results revealed that the effect of using high strength concrete versus normal strength concrete in the composite prisms was negligible.
- The test results revealed that the degradation in flexural capacity was reduced by an increase in the fibre volume content.

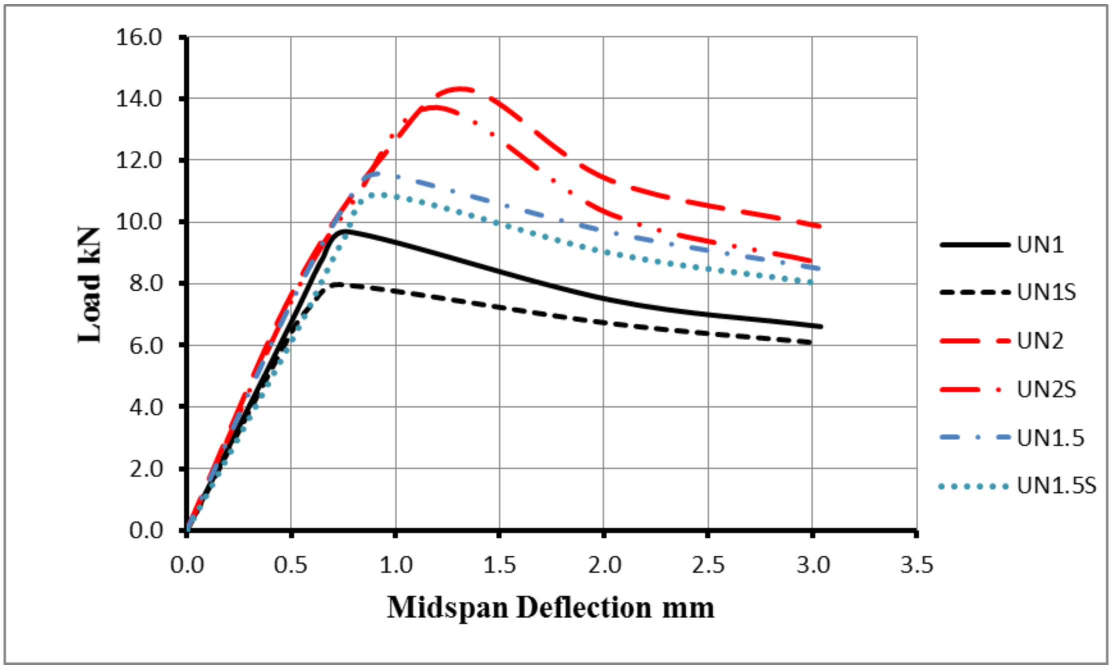

Figure 3: Mid span deflection vs load for UHPFRC-NSC members

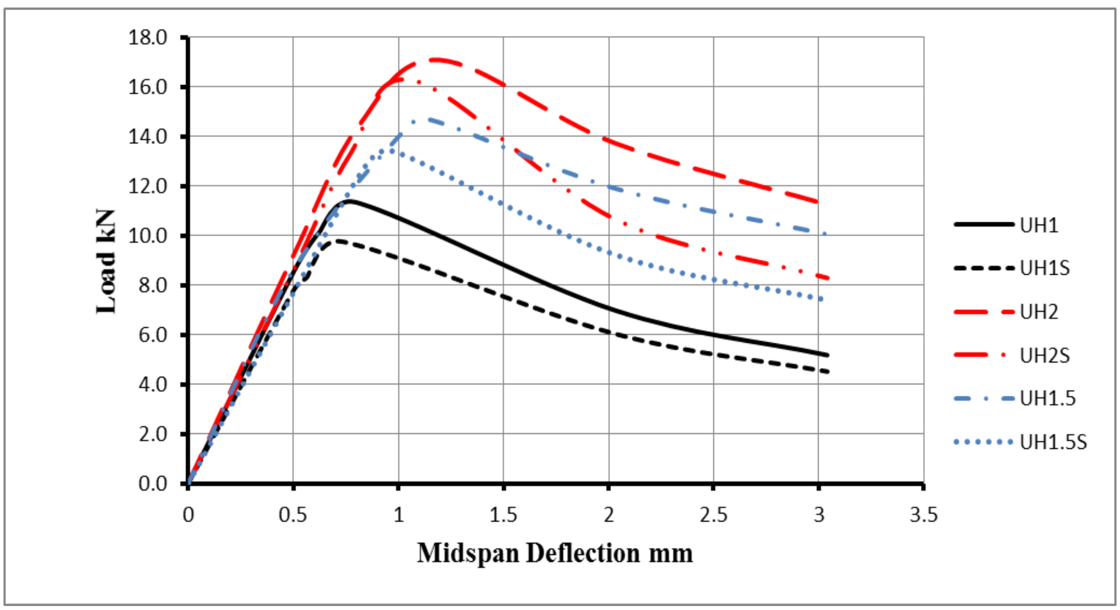

Figure 4: Mid span deflection vs load for UHPFRC-HSC members

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